1997

Determining a dynamic strength reduction factor for regular slotted containers

Sabine Nicole Prather
San Jose State University

DETERMINING A DYNAMIC STRENGTH REDUCTION FACTOR FOR REGULAR SLOTTED CONTAINERS

A Thesis

Presented to

The Faculty of the Department of Nutrition and Food Science

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Sabine Nicole Prather

December 1997

UMI Number: 1388209

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

APPROVED FOR THE DEPARTMENT

OF NUTRITION AND FOOD SCIENCE

J Marcondes

Dr. Jorge Marcondes

Lucy McProud

Dr. Lucy McProud

Miriam Saltmarch

Dr. Miriam Saltmarch

H Schueneman

Mr. Herb Schueneman

APPROVED FOR THE UNIVERSITY

William Fish

ABSTRACT

DETERMINING A DYNAMIC STRENGTH REDUCTION FACTOR

FOR REGULAR SLOTTED CONTAINERS

by Sabine Nicole Prather

Regular Slotted Containers (RSCs) were subjected to dynamic compression using random vibration and top loads to simulate stacked packages in a vehicle during transport. Several levels of vibration intensity were applied to top loaded RSCs which had been conditioned at standard humidity and temperature conditions. Results show that the intensity of vibration has significant influence on the top load a corrugated fiberboard package can withstand during distribution. RSCs failed with much less top load when subjected to higher vibration levels. These results suggest the establishment of "dynamic strength reduction factors" to be used for corrugated fiberboard packaging design.

ACKNOWLEDGMENTS

I would like to thank my graduate advisor Dr. Jorge Marcondes for his encouragement, countless hours of help, and guidance. I am also very grateful to Mr. Herb Schueneman of Westpak, Inc. for always taking the time to answer my questions and guide me. I would also like to express my gratitude to the other members of my graduate committee, Dr. Lucy McProud and Dr. Miriam Saltmarch who also made time despite their hectic schedules, to guide me through the graduate program.

I am indebted to THARCO for the donation of the RSCs and Westpak, Inc. for the use of all the equipment.

PREFACE

The following is a publication style thesis. The second chapter is written in journal format and will be submitted to the *Technical Association of the Pulp and Paper Industry (TAPPI) Journal*. Chapter 1 and 3 are written according to guidelines outlined in the *Publication Manual of the American Psychological Association*, 4th edition, 1994.

Table of Contents

List of Figures

List of Tables

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

Introduction

Corrugated fiberboard is the most common distribution container material, and the regular slotted container (RSC) is the most commonly used container design for distribution packaging (Soroka, 1995). Boxes, containing products, are stacked several high in warehouses and vehicles. Compression strength is important because it is used to estimate the performance of corrugated boxes during stacking. Compression strength is defined as the maximum load that can be applied to a container under specified conditions. More specifically, compression is the top to bottom strength of a box measured in a laboratory under quasi-static compression at standard conditions (73° F and 50% R.H.) (Surber and Catlin, 1982).

Compression strength has been widely studied over many decades. However, most studies have concentrated on techniques to measure compression strength, or on the effect of impacts on compressive performance (Langlois, 1989; Crofts, 1989). Standard compression results reflect neither the time it takes for boxes to fail nor the effects of dynamic compression (compression due to the rapid application of a load), as seen when boxes are stacked and transported.

Truck transport is considered the most severe of any input likely in the distribution environment (Ostrem & Godshall, 1979) and boxes are commonly stacked up to 110 inches (American Society for Testing and Material [ASTM] D4169-93). Vibration occurs mainly due to irregularities of road pavements and internal vibrations of vehicles (Marcondes & Feather, 1992). Every product in transport receives vibration. The corrugated box is elastic and therefore acts as a spring when loaded and exposed to vertical vibration (Guins, 1975). On the road, trucks encounter potholes or other rough surfaces and vibrate in a complex manner, both in intensity and frequency. The weight of the stack of boxes combined with vibration causes the bottom box to be subjected to a very high dynamic force. If this dynamic force is greater than its compression strength, the box will fail by collapsing. When box failure occurs during transport, it is usually at the bottom box in the stack (Adams, 1987). When a box in a stack fails, the entire stack may fall and damage the products the boxes contain, nearby objects, people, etc. By simulating a distribution environment in a laboratory a dynamic strength reduction factor can be discovered and used to prevent loss of product, as well as loss of dollars due to unnecessary over packaging.

Random vibration can be used to determine a dynamic strength reduction factor; which can be used for design of packages. A vehicle ride may be simulated by a closed loop controlled vibration test system. Through the use of dedicated software and hardware, a vibration table can be driven in closed loop. In this closed loop, the response of the table is monitored (with the use of an accelerometer) and fed back into the controller so adjustments can be made to the table in order to run the preprogrammed random vibration spectrum (or demand profile) to simulate vehicle rides.

Box design is done today only using a safety factor; a factor which accounts for length of stacking time, humidity, pallet size, stacking pattern, the care taken in stacking, and the value of the product. There is a need to find ways to also consider in the design the specific effects of dynamic inputs.

Objectives

This study was conducted: (1) to determine a dynamic strength reduction factor by testing dynamic performance of RSCs to failure, and then relating this to standard lab compression strength; (2) to find if box size has any effect on the strength reduction factor; and (3) to find the resonant frequency of the RSCs with varying top loads during random vibration.

Review of Literature

Static Compression Strength

Compression strength can be measured in a lab or estimated. It is important to measure compression strength at standard conditions as compression strength decreases as humidity increases (Kellicutt & Landt, 1951). McKee (1963) developed the most widely used calculation in estimating static compression strength. McKee's formula relates Edge Crush Test (ECT) values to expected box compression strength. A simplified version of this formula is:

$$5.87 \times \text{ECT} \times (\text{BP} \times \text{T})^{0.5} \qquad (1)$$

where BP = inside box perimeter (in.), T = combined board thickness (in.), ECT = Edge Crush Test, determined in a laboratory testing a sample of the corrugated fiberboard the RSC is made of (lb./in.).

Quasi-static compression strength laboratory tests and estimations from McKee's formula only predict the container's ability to withstand an instant stationary load. Surber and Catlin (1982) explain a "safety factor" designed to account for real life (static) situations encountered in stacking. This factor takes into account length of stacking time, humidity, pallet size, stacking pattern, the care taken in stacking, the value of the product and other factors; and is calculated by dividing the box strength by the actual weight on each bottom box. This safety factor still only takes into consideration static compression strength, and does not account for dynamic inputs in transport.

Dynamic Compression Strength

The ASTM standard D 4169-96 recommends "F" factors for vehicle stacking. These are intended to determine the ability of the shipping unit to withstand the compressive loads that occur during transport in carrier vehicles; or dynamic compression strength. The effects of time and vibration in transport, the alignment or stacking pattern of the container, variability in container strength, moisture content, temperature, previous handling, and method of load support are all taken into account in these factors. The factors intended to account for dynamic forces are recommended in ASTM standard D4169-96 for a corrugated container and are shown in Table 1.

Table 1

Safety Factors Recommended by D4169-96 for Vehicle Stacking

Shipping Unit Construction	Assurance Level		
(Condensed description)	I	II	III
1. Corrugated where product does not support any of the load	10.0	7.0	5.0
2. Corrugated with stress-bearing interior packaging with rigid inserts (such as wood)	6.0	4.5	3.0
3. Other than corrugated - not temperature or humidity sensitive, or when the product supports the load directly	4.0	3.0	2.0

Note. Adapted from American Society for Testing and Materials Standard D4169-96, 1996.

Vibration Effects on Corrugated Fiberboard

Random vibration is a continuous oscillating motion whose instantaneous amplitude can be predicted only on a probability basis. (Pennington, 1966). The vibration encountered by trucks and rail cars has been successfully simulated in laboratories using random vibration. Generally, the highest vibration level in trucks occurs in the vertical direction and between 2-16 Hz. However, during random vibration the frequencies are constantly changing and different frequencies are occurring at the same time. The G rms level (root mean square acceleration in Gs, where 1 G = 386in/s^2) is an average of all of the acceleration peaks in the vibration. Standard G rms levels used in short laboratory tests to simulate real life lengthy truck rides range from 0.53 G rms (ASTM D-4169 test standard, 1996) to 1.15 G rms (International Safe Transit Association [ISTA] 2A test standard, 1996). Figure 1 shows a typical random vibration spectrum.

W.D. Godshall (1968) examined the effects of vertical dynamic loading on corrugated fiberboard boxes. Various percentages of average compression strengths for the boxes were placed on a single empty box. The boxes were then subjected to sinusoidal vibration (a repetitive pattern of vibration where the positive displacement equals the negative displacement), not necessarily to failure. He concluded that container failure was primarily due to dynamic overload, and not to fatigue. He expected to find that S-N curves (curves expressing stress (lb.) in the y axis and number of vibration cycles in the x axis) could be developed for dynamic loading data. Instead, he discovered they would have little meaning due to the nature of the failures that occurred. In general, the containers either failed at the beginning of the test, with only a few cycles of loading, or they survived the entire test without apparent damage. When subjected to random vibration excitation, failure occurs as a result of the combined effect of stress cycles of many different amplitudes. The S-N curve is a formerly used linear method to predict failure which applies to a wide range of materials, but not to corrugated containers subjected to random vibration (Newland, 1984).

Urbanik (1990) studied the effect of sine vibration on top loaded corrugated RSCs. He determined that the force-deformation response of corrugated containers is highly nonlinear. He also found, because corrugated fiberboard is highly sensitive to loading

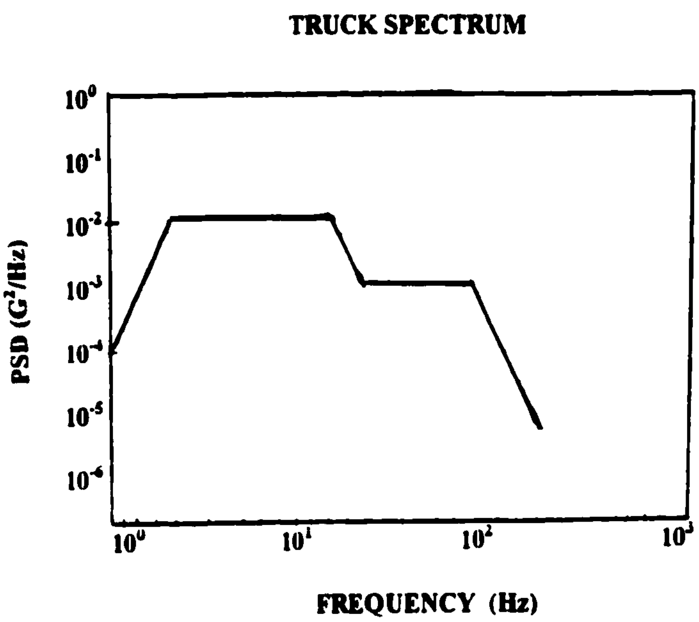

Figure 1. Typical random vibration spectrum for truck transport (ASTM D-4169, 1996)

rate, that its load-deformation curve from a compressive strength test is a poor predictor of stiffness.

<u>Resonant and Natural Frequencies of Corrugated Fiberboard</u>

Adams (1987) studied the effect of resonant vibration on the compression strength of corrugated fiberboard boxes. He found that there was an 8% increase in compression strength as the boxes "squared up" at resonance, because the height of each support column was discovered to become similar.

Kusza and Young (1974) studied vibration response of packages stacked in a column. They concluded that a greater number of boxes in a stack results in a lower natural frequency for the stack.

Godshall (1968) found the natural frequency of most boxes to be between 10-15 Hz. He discovered that as boxes are stacked the natural frequency of the stack reduces at a rate proportional to the square root of the number of containers in a stack.

<u>Preliminary Work</u>

Marcondes (1996) conducted preliminary studies on regular slotted C flute corrugated fiberboard boxes with internal dimensions of 20" x 12" x 9". The boxes were separated into four groups and conditioned to represent standard, high humidity, tropical, and chilled storage conditions. The boxes were then compression tested and various dead loads lower than the values found in the static compression test were used as top loads on the boxes. The ASTM D-4169-93 Element G truck spectrum was used to simulate road transport and packages were subjected to five minutes at each one of the following G rms levels until failure: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, etc. At standard conditions, a dead load of 10-20% of the compression strength, the maximum G rms level the package could sustain without failure was 0.6 G rms. For a dead load of 24-42% of the compression strength, the maximum G rms level before failure was 0.3 G rms. With 40% of the compression strength top loaded on the boxes the maximum G rms level before failure was 0.2.

CHAPTER 2

JOURNAL ARTICLE

This article is to be submitted to the

Technical Association of the Pulp and Paper Industry Journal

and, therefore, has a different format from that of Chapters 1 and 3.

DETERMINING A DYNAMIC STRENGTH REDUCTION FACTOR FOR REGULAR SLOTTED CONTAINERS

Sabine N. Prather
Packaging Graduate Student
San Jose State University
San Jose. CA 95192-0058

Jorge Marcondes. Ph.D.*
Associate Professor. Packaging Program
San Jose State University
San Jose. CA 95192-0058

Lucy McProud. Ph.D.
Nutrition & Food Science Dept. Chair
San Jose State University
San Jose. CA 95192-0058

Miriam Saltmarch. Ph.D.
Professor
San Jose State University
San Jose. CA 95192-0058

Herb Scheuneman. CPP
President Westpak. Incorporated
San Jose. CA 95119

* Author to address questions and comments to

ABSTRACT

Regular Slotted Containers (RSCs) were subjected to dynamic compression using random vibration and top loads to simulate stacked packages in a vehicle during transport. Several levels of vibration intensity were applied to top loaded RSCs which had been conditioned at standard humidity and temperature conditions. Results show that the intensity of vibration has a significant influence on the top load a corrugated fiberboard package can withstand during distribution. RSCs failed with much less top load when subjected to higher vibration levels. These results suggest the establishment of "dynamic strength reduction factors" to be used for corrugated fiberboard packaging design.

INTRODUCTION

In distribution. packages are stacked for warehouse storage and vehicle transport. It is not uncommon to find warehouse stacking of three pallet loads or heights of 5 or 6 meters (1). In vehicles. stacks are generally limited by the internal height of the vehicles. which can be up to 2.5 meters. The stacking of packages causes compressive forces to act on the packages lower in the stack.

For warehouse storage. the bottom package in the stack receives the highest compression force. For example. a stack of 10 packages of 10 kg. each would apply 883 N on the bottom package in the stack. Therefore. the bottom package should be able to withstand at least 883 N at all times. otherwise the stack could collapse.

For packages stacked and transported in a vehicle. the lowest package may not always receive the highest compression force all the time. This depends on the mechanical characteristics of the stack and how the impacts and vibration levels are transmitted from the floor of the truck to the higher packages. In any case. packages in a stack need to sustain the weight of the products inside them as well as any weight stacked on top of the packages. Currently. warehouse stacking is only considered when designing packages. This does not consider the dynamic forces a package receives when stacked in a vehicle. The objective of the research reported in this paper was to determine a dynamic strength reduction factor to account for the oscillation in dynamic forces of a stack of packages in a vehicle in motion. Although a stack of packages is a multiple degree of freedom system. this experiment was conducted as a single degree of freedom system for simplicity.

Experiments were conducted with regular slotted containers (RSCs) under standard temperature and humidity conditions (2). The objective was to determine: (i) a dynamic strength reduction factor by testing dynamic performance of top loaded RSCs at various vibration levels to failure, and then relating this to standard lab compression strength; (ii) to find if box size has any effect on the strength reduction factor; and (iii) to find the resonant frequency of the RSCs with varying top loads during random vibration.

BACKGROUND

The forces in a stack of boxes within a vehicle are different from those in a warehouse because of the motions encountered in a vehicle. The up and down movement of the vehicle floor imposes impacts and vibrations on the packages. When vibration levels exceed 1 G, those packages that are not restrained to the vehicle floor will bounce; causing impacts. These impacts can have acceleration levels much higher than 1 G. Although this force only occurs momentarily, it is necessary that the bottom package withstands it, whenever it occurs. If not, the bottom package will fail and the stack will collapse.

The vibration encountered by trucks and rail cars has been successfully simulated in laboratories using random vibration. Generally, the highest vibration level in trucks occurs in the vertical direction and between 2-16 Hz. However, during random vibration the frequencies are constantly changing and different frequencies are occurring at the same time. The G rms level (root mean square acceleration in Gs, where 1 G = 9.81 m/s^2) is an average of all of the acceleration peaks in the vibration. Standard G rms levels used in short laboratory tests to simulate real life lengthy truck rides range from 0.53 G rms (3) to 1.15 G rms (1).

A vehicle ride may be simulated by a closed loop controlled vibration test system. Through the use of dedicated software and hardware, a vibration table can be driven in closed loop. In this closed loop, the response of the table is monitored (with the use of an accelerometer) and fed back into the controller so adjustments can be made to the table in order to run the preprogrammed random vibration spectrum (or demand profile). Random vibration can be used to determine a dynamic strength reduction factor; which can be used for design of packages.

Box design is done today only using the strength reduction factor (SRF): a factor which accounts for length of stacking time, humidity, pallet size, stacking pattern, the care taken in stacking, and the value of the product. There is a need to find ways to also consider in the design the specific effects of dynamic inputs.

MATERIALS AND METHODS

Three sizes of single wall corrugated regular slotted containers (RSCs) were used. The internal dimensions of each box were as follows: Box 1: 15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4"), Box 2: 20.32 cm x 15.24 cm x 10.16 cm (8" x 4" x 4"), and Box 3: 24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4"). All of the boxes had a minimum 5.6 kN/m (32 lb./ in.) for the ECT, and had a burst strength of at least 1.379 kPa (200 lb./in.^{2}). The boxes were all sealed with pressure sensitive clear tape.

The boxes were received knocked down flat with a glued manufacturer's joint from THARCO (San Lorenzo, CA). They were then preconditioned at 23° C at 35% relative humidity in a Tenney Model TH-36 environmental chamber for 24 hours. After 24 hours, the humidity was increased to 50%, and the temperature remained at 23° C (Standard laboratory conditions, 2).

Bursting Strength Testing

Bursting strength is primarily an indication of the character of the materials used in manufacturing a fiberboard box (4). Specimens were cut from boxes not used for any other tests to evaluate bursting strength for each of the different sized boxes. Specimens were cut and tested in accordance with TAPPI standard T 810 om-92 (4). The samples were tested on a Mullen tester which punctures the sample to determine its strength (measurement is in kPa).

Edge Crush Testing

Specimens were cut from samples not previously tested. First the specimens were cut into 5.08 cm (2 inch) sections on a Lorentzen and Wettre Model 513 machine. Then they were cut neck down on a Lorentzen and Wettre Model 120 machine and tested in accordance with ASTM standard D 2808-96 (5). The specimens were tested on a Lorentzen and Wettre Crush Tester Model 336.

Moisture Content

Three specimens were cut and tested to determine moisture content. ASTM D644-94 (6) procedures were followed. An Allied drying oven was used to dry the samples. The oven was set at 100°C. and throughout the day the oven remained constant at 100°C. After 11 hours. the samples were removed from the oven and reweighed.

Compression Test

After the preconditioning and conditioning, 5 randomly chosen samples from each box size were compression tested (empty) with an Instron Tensile/Compression Tester Model TTC. The Instron has a fixed platen and a Hewlett-Packard Model 7045B x-y recorder. The crosshead speed of the machine was 1.27 cm per minute (7).

By averaging the five compression strength values obtained for each box size. top loads were determined using various percentages (see Tables 1 and 2). The percentages corresponded to a strength reduction factor (SRF) that was determined for each box design. The purpose of the strength reduction factor was to estimate the ultimate compression strength of boxes. The following equation is often used for ultimate compression strength in transport: $Cs_u = CS/SRF$ (8). where Cs_u = ultimate compression strength (kg). CS = laboratory determined compression strength (kg). SRF = strength reduction factor.

Table 1. Compression strength of boxes

	15.24 cm x 10.16 cm x 10.16 cm Box 1 (6" x 4" x 4")	**20.32 cm x 10.16 cm x 10.16 cm Box 2 (8" x 4" x 4")**	**25.4 cm x 15.24 cm x 10.16 cm Box 3 (10" x 6" x 4")**
Compression Strength per ASTM D642. N (lb.)	1579 (355)	1602 (360)	1846 (415)
Estimated Compression Strength*. N (lb.)	1321 (297)	1446 (325)	1673 (376)

* Using McKee's formula (9)

Dynamic Compression Strength of Boxes with Varying Top Loads

Boxes were sealed using pressure sensitive tape and calculated loads were placed on top of each empty box. Five boxes of each size were subjected to the ASTM D4169-96 Element G truck spectrum (3) at intensity levels beginning at 0.2 G rms. for a period of 300 seconds. and increasing in intensity up to the failure point. Seventy-five boxes were subjected top loaded vibration. Table 2 shows the load placed on each of the different sized boxes.

Table 2. Total load placed on boxes

% of Mean Lab Compression Strength	Strength Reduction Factor*	15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	25.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4")
10	10	16.1 (35.5)	16.3 (36)	18.8 (41.5)
15.8	6.3	56.4 (25.6)	56.9 (25.9)	65.6 (29.8)
22.6	4.4	36.6 (80.6)	36.9 (81.4)	42.5 (93.4)
33	3	53 (117.2)	53.9 (118.8)	62 (137)
50	2	80.5 (177.5)	81.7 (180)	94.1 (207.5)

* Calculated as the inverse of the % mean lab compression strength

The weights comprising the loads were fastened inside an aluminum "piston" weighing 11.3 kg (See Figure 1). Two threaded rods on the inside of the piston held the weights. Immediately after the load was placed onto the boxes, they were subjected to the D-4169-93 (detailed in the American Society for Testing and Materials Specifications) truck random vibration spectrum (3). Vibration was started at the 0.2 G rms level for 5 minutes and increased in intensity until the box failed. A GenRad Model 2532 vibration controller was programmed to vibrate at each of the following G rms levels: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, etc., for 5 minutes each, or until failure. A timer on the vibration controller was used to record the period of time at various G rms levels at which box failure occurred. Hot melt adhesive was used to adhere an accelerometer to the top of the weight system to measure the resonance of the spring mass system consisting of the weighted "piston" (mass) and the corrugated box (spring).

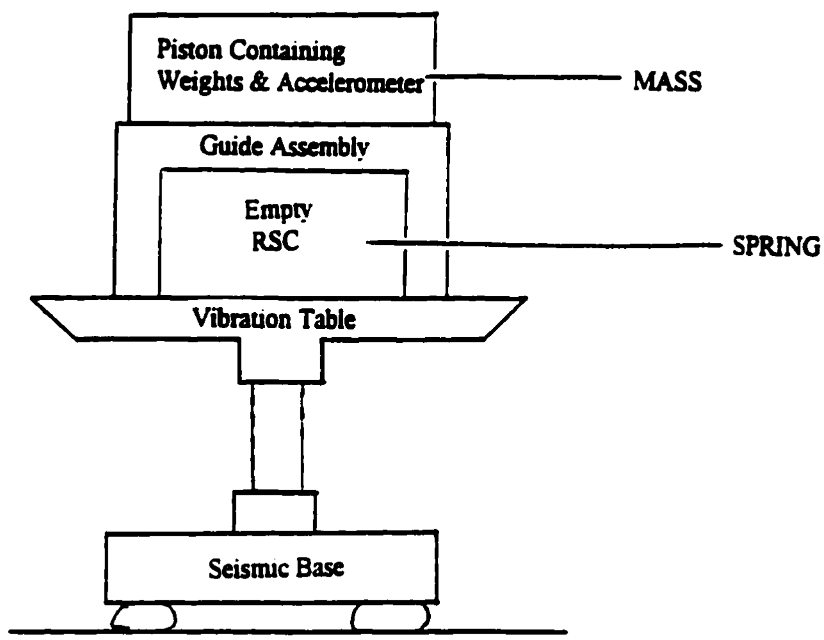

Figure 1. Fixture configuration

Vibration tests were performed at each G rms level of 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7. Each level was maintained for 300 seconds, or until failure, and then increased to the next level (if failure did not occur). Power density levels at each break point in the vibration spectrum for a 0.5 G rms level are seen in Table 3.

Table 3. Random vibration spectrum break points

Break Point	Frequency (Hz)	Power Density (g^2/Hz)
1	1	0.0001
2	4	0.01
3	16	0.01
4	40	0.001
5	80	0.001
6	200	0.00001

RESULTS

Bursting strength & Edge crush test (ECT)

Three samples from each box size were tested for bursting strength. An average of the results for each box size are contained in the Table 4.

Table 4. Bursting Strength of Boxes

Box Size	Mean	Standard Deviation
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	1503 kPa (218 lb./in^2)	± 20.4
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	1693.8 kPa (245.7 lb./in^2)	± 22.7
24.4 cm x 15.24 cm x 10.16 cm (10 x 6" x 4")	1413.4 kPa (205 lb./in^2)	± 10

Edge crush testing (ECT) was completed on 5 samples from each of the three boxes. Mean results can be found in Table 5.

Table 5. Mean Edge Crush Test (ECT) Results

Box Size	Mean	Standard Deviation
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	5.7 kN/m (32.8 lb./in.)	± 3.5
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	7.4 kN/m (42.1 lb./in.)	± 2.5
24.4 cm x 15.24 cm x 10.16 cm (10 x 6" x 4")	6.2 kN/m (35.3 lb./in.)	± 1.8

Moisture Content

Moisture content was determined as specified in ASTM D 644-94 (6). One sample was taken from each of the box sizes. After the samples were completely dry, they were removed and reweighed. Throughout the day, the oven temperature was constant at 100°C.

Table 6. Moisture content (wet basis) of samples

Box Size	Wet basis (%)
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	8.12
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	7.71
24.4 cm x 15.24 cm x 10.16 cm (10 x 6" x 4")	8.41

Mean: 8.08
Standard. deviation = 0.35

Dynamic Strength Reduction Factor

Seventy-five corrugated fiberboard RSCs were tested to failure to determine a dynamic strength reduction factor for each compression strength. Results are summarized in Table 7.

Table 7. Average G rms level at failure for each strength reduction factor (SRF)

Box size	Dynamic SRF	% Load	Average G rms Level at Failure
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	10	10	0.6
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	10	10	0.66
24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4")	10	10	0.62
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	6.3	15.8	0.5
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	6.3	15.8	0.5
24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4")	6.3	15.8	0.5
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	4.4	22.6	0.46
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	4.4	22.6	0.40
24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4")	4.4	22.6	0.40
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	3	33	0.40
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	3	33	0.32
24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4")	3	33	0.34
15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4")	2	50	0.22
20.32 cm x 10.16 cm x 10.16 cm (8" x 4" x 4")	2	50	0.20
24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4")	2	50	0.22

* Failed while ramping up to G rms level 0.4. Survived the full 300 seconds of 0.3 G rms level.

The failure patterns of the boxes were very consistent. As expected. the percentage top load had an inverse relationship with the G rms vibration level. For RSCs sized between 15.24 cm x 10.16 cm x 10.16 cm (6" x 4" x 4") and 24.4 cm x 15.24 cm x 10.16 cm (10" x 6" x 4") loaded with 10% of the box compression strength. failure can be expected during the 0.6 G rms level. For boxes of the same size loaded with 15.8% of the compression strength the failure should be expected to occur during the 0.5 G rms level. When loaded with 22.6% of the compression strength the boxes most likely will fail before reaching the 0.5 G rms level. For a 33% load. failure can be expected to occur before full level at 0.4 G rms. When loaded with 50% of the compression strength. failure can be expected to occur shortly into the 0.2 G rms level.

Resonance of the boxes before failure

Resonance of the 75 boxes was monitored with the use of a PCB model A 353-15 accelerometer mounted to the upper most weight with hot melt adhesive in the aluminum piston. The corrugated box is elastic and therefore acts as a spring when loaded and exposed to vertical vibration (10). Resonance was determined by identifying the frequency where the response acceleration was at its highest transmissibility. Generally. resonant frequencies decreased as the top load on the boxes increased. Godshall in 1968 found the natural frequency of most boxes to be between 10-15 Hz (11). In this study. the boxes were found to have a resonant frequency ranging from 22-55 Hz. One explanation for this difference in findings could be Godshall used sine sweep vibration. which has been shown to cause a "jump" in resonant frequencies.

Application

This research in determining a dynamic strength reduction factor (DSRF) has many useful applications. The dynamic strength reduction factor can be used to estimate the strength necessary for a corrugated box to support a load when in distribution. Figure 2 shows overall G rms level vs. Load and DSRF for all boxes. This can be applied in designing and testing corrugated fiberboard boxes. A study of the expected distribution environment will allow an estimation of the G rms level anticipated. Figure 2 can be used to find an approximate DSRF. For example: If in truck transport. stacks of n boxes are expected. then:

$$F = (n-1)(w) \qquad (1)$$

where F= force on bottom box. w= weight of each box. Compression strength required can be calculated by (F) x (DSRF). This compression strength required can then be used for design (with the use of McKee's formula) and for testing using a compression tester. For example. a company uses 0.53 G rms to conduct a short laboratory vibration test to simulate a long truck haul on 10 boxes weighing 100 N each. The force on the bottom box would be: F = (10-1) x (10 N) = 900 N. Then using Figure 2. the DSRF can be determined to be 7. Using the formula (F) x (SRF) = (7) x (900 N) = 6300 N. Therefore. the box must have a compression strength of at least 6300 N.

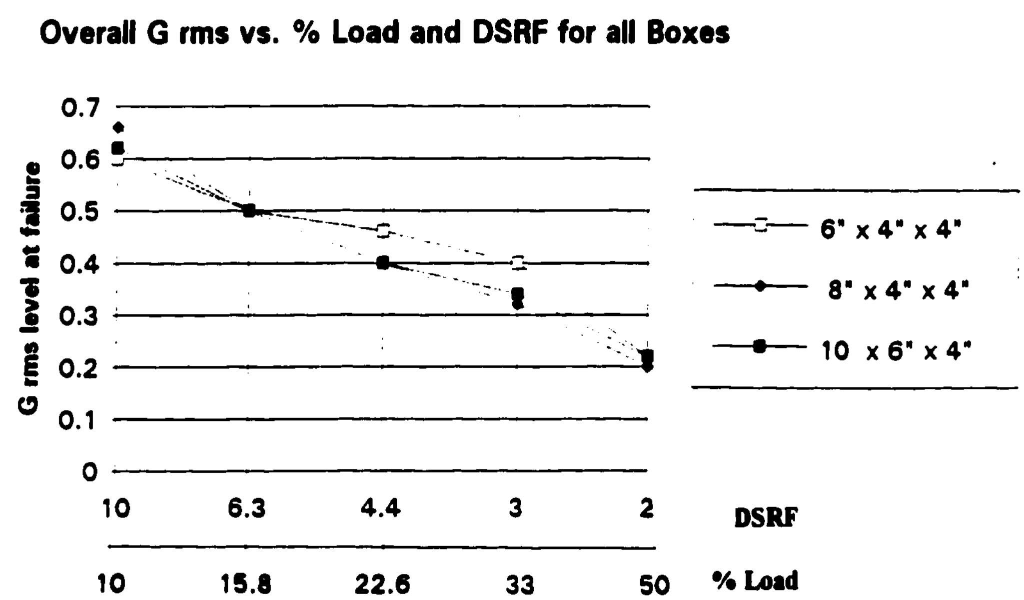

Figure 2. Overall G rms level vs. Load and DSRF for all boxes

CONCLUSIONS

The conclusions of this study are:

A dynamic compression test using random vibration showed that. as the dead load increases the total duration of vibration before package failure will decrease. In addition. as dead load increases. there is a reduction in the G rms level at which failure occurs. for similar test durations: Using the dead load weights and the G rms for each test. a "dynamic strength reduction factor" can be determined. This factor can be estimated between 2 for smooth roads and 10 for rough roads.

Although the top loaded fixture does not produce realistic dynamics of a stacked column in a vehicle. this approach offers an indication that a large reduction in strength occurs when a vehicle vibrates vertically. as always occurs in truck transport. This reduction factor will account for the vibration compression forces that will be imposed on the boxes in the stack during transport.

REFERENCES

1. International Safe Transit Association. *Procedure 2A Preshipment Test Procedures*, East Lansing. MI. 1996.

2. ASTM. *Selected ASTM Standards on Packaging, (D-4332), 3rd. ed.*, AMERICAN SOCIETY FOR TESTING AND MATERIALS. Philadelphia. 1989. p.251-252.

3. ASTM. *Selected ASTM Standards on Packaging (D-4169), 4th ed.*, AMERICAN SOCIETY FOR TESTING AND MATERIALS. Philadelphia. 1993. p.237-247.

4. ASTM. *Selected ASTM Standards on Packaging, (TAPPI T-810-om 89), 3rd. ed.*, AMERICAN SOCIETY FOR TESTING AND MATERIALS. Philadelphia. 1989. p.351-354.

5. ASTM. *Selected ASTM Standards on Packaging, (D-2808), 3rd. ed.*, AMERICAN SOCIETY FOR TESTING AND MATERIALS. Philadelphia. 1989.

6. ASTM. *Selected ASTM Standards on Packaging (D-644-89), 4th ed.*, AMERICAN SOCIETY FOR TESTING AND MATERIALS. Philadelphia. 1993. p.19-20.

7. ASTM. *Selected ASTM Standards on Packaging, (D-642), 4th ed.*, AMERICAN SOCIETY FOR TESTING AND MATERIALS. Philadelphia. 1993. p.8-11.

8. Marcondes. J.A., *Packaging Technology and Engineering*, "Virgin vs. recycled corrugated: similar compression strengths." 1: 29-52 (1996).

9. McKee. R.C., Gander. J.W., Wachuta. J.R., *Paperboard Packaging*, "Compression strength formula for corrugated boxes." 8 (1963).

10. Newland. D.E., *An Introduction to Random Vibration and Spectral Analysis*, 2nd. ed., LONGMAN. New York. 1984. p.55.

11. Godshall. W.D., *Forest Products Laboratory*, "Effects of vertical dynamic loading on corrugated fiberboard containers." FPL 94. 1-19 (1968).

ACKNOWLEDGMENTS

The author would like to acknowledge the assistance of THARCO for providing the RSCs used in this study and Westpak. Incorporated for the use of all the testing equipment. Thanks are also extended to Data Physics Corporation for providing a grant to fund the random vibration controller used in preliminary testing for this study. Also, thanks are extended to Dr. Jorge Marcondes and Mr. Herb Schueneman for their countless hours of advice, patience, and help with this research.

CHAPTER 3

DISCUSSION, SUMMARY, AND RECOMMENDATIONS

Discussion

This section includes an extended analysis of the results obtained in the vibration tests when 10%, 15.8%, 22.6%, 33%, and 50% loads of lab compression strength were placed on the empty boxes. Figures 2, 3, and 4 show a graphic representation of the findings. The G rms points, plotted in the vertical axes, were obtained in two ways: a) if failure occurred while ramping up to a G rms level, then this level was used in plotting the point, b) when failure occurred during a time (t), in seconds (s), at a particular G rms level, then the level to make the point was calculated as:

$$\text{G rms level} + 0.1 \times t\,(s)/300. \qquad (2)$$

<u>10% Mean Lab Compression Strength</u>

The 6" x 4" x 4" box had an actual compression strength average of 355 lb. when tested in the lab. Five samples of this box size were loaded with 35.5 lb. (10% of 355 lb.). while being subjected to a truck random vibration spectrum from 1-200 Hz, as per ASTM D4169-93 (ASTM, 1994). Each of the five boxes sustained 300 seconds at 0.2 G rms, 300 seconds at 0.3 G rms, 300 seconds at 0.4 G rms, and 300 seconds at 0.5 G rms. However, the boxes failed between 185-300 seconds after the start of 0.6 G rms (See Appendix A-1).

The 8"x 4"x 4" box had an actual lab tested compression strength average of 360 lb. Five samples, loaded with 36 lb. each, were subjected to the D4169-93 truck random

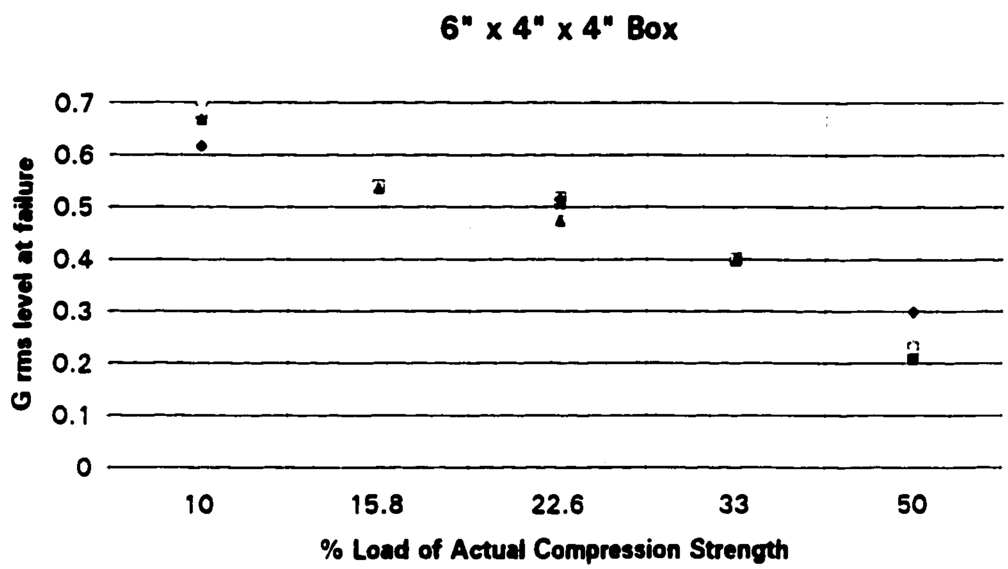

Figure 2. 6" x 4" x 4" Box G rms vs. % Load

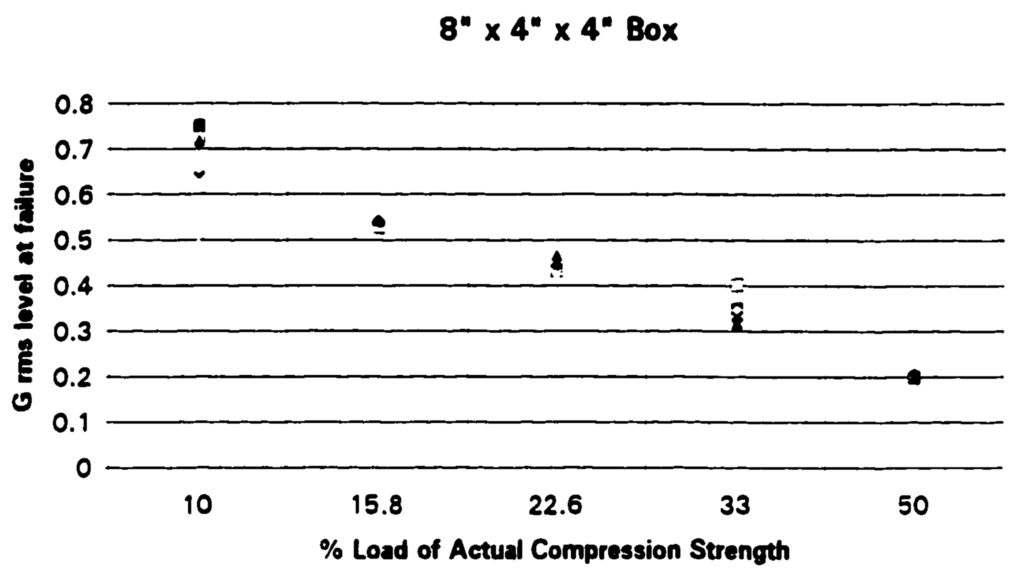

Figure 3. 8" x 4" x 4" Box G rms vs. % Load

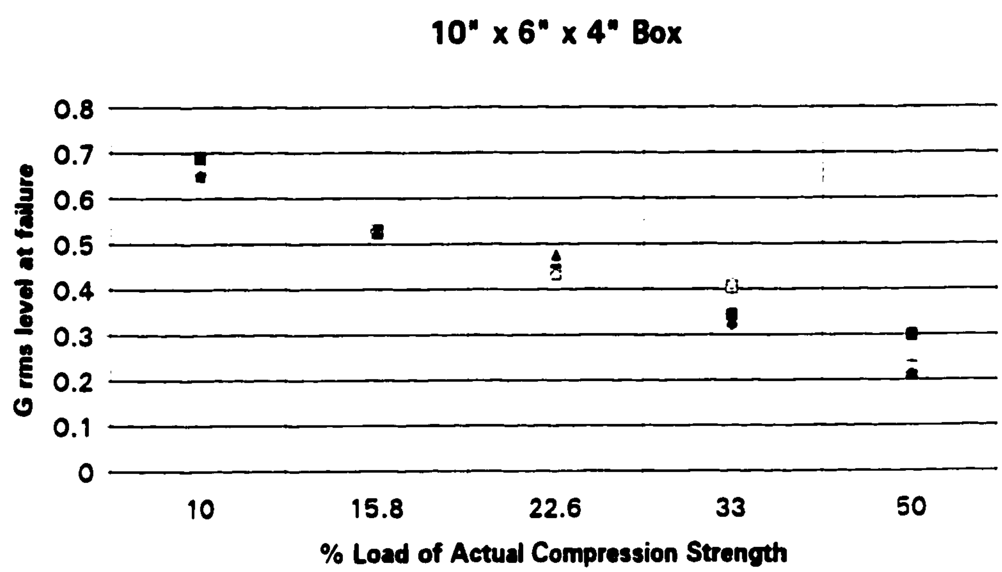

Figure 4. 10" x 6" x 4" Box G rms vs. % Load

vibration spectrum. The boxes survived 300 seconds for each 0.2, 0.3, 0.4, 0.5 G rms. Three boxes withstood G rms levels of 0.6 for 300 seconds each, only failing at 0.7 G rms after 151 seconds, 76 seconds, and 53 seconds. The other two boxes failed during the 0.6 G rms level after 139 seconds and 164 seconds (See Appendix A-1).

The largest box size, 10" x 6" x 4", loaded with 41.5 lb. (10% of 415 lb.) showed similar results to the 6" x 4" x 4" and the 8" x 4" x 4" boxes mentioned previously. Four of the five samples with a load of 41.5 lb. sustained 300 seconds at each 0.2, 0.3, 0.4, and 0.5 G rms and failed during the 0.6 G rms level between 152-269 seconds. The fifth box lasted through the entire 300 seconds at 0.6 G rms and 54 seconds into the 0.7 G rms level before failure occurred (See Appendix A-1).

All boxes subjected to a 10% load of the compression strength failed either during the 0.6 G rms level (6" x 4" x 4" box) or during the 0.7 G rms level (See Appendix A-1). In the study completed by Marcondes (1996) he discovered for a dead load of 10-20% lab determined compression strength the maximum G rms level the package could sustain without failure was 0.6 G rms. This is essentially what was discovered in this research.

15.8% Mean Lab Compression Strength

The smallest box size, 6" x 4" x 4" , was subjected to a load of 56 lb., or 15.8% of the actual compression strength. All five boxes failed during the 0.5 G rms level, with failure times varying from 77 seconds to 115 seconds (See Appendix A-2).

The 8" x 4" x 4" box was also subjected to a load 15.8% of the actual compression strength, or 57 lb. Like the smaller box, failure occurred at 0.5 G rms in each of the 5 samples. Time to failure ranged from 53-164 seconds (See Appendix A-2).

Sixty-six pounds were loaded onto the 10" x 6" x 4" box, representing 15.8% of its compression strength. As seen in the other two box sizes, failure occurred for all 5 box samples during the 0.5 G rms level. The time for box failure was very close between all the 5 box samples, varying only from 71-91 seconds (See Appendix A-2).

As all fifteen boxes, in the three sizes, failed between approximately 60 and 150 seconds during the 0.5 G rms level, it can be deduced that failure with these box sizes is eminent between 60-180 seconds with a load of 15.8% of the actual compression strength of the box (See Appendix A-2). Again, Marcondes (1996) discovered that the maximum level a package loaded with 10-20% of the compression strength an empty box could sustain without failure was 0.5. This matches the findings of this research.

22.6% Mean Lab Compression Strength

The next loading to which each of the boxes was subjected was 22.6% of the average actual compression strength. For the 6" x 4" x 4" box, this weight was calculated to be 80.58 lb. Under a load of 80.58 lb., two boxes survived 300 seconds at 0.2, 0.3 G rms. Failure occurred with these two boxes after 271 seconds and 228 seconds at the 0.4 G rms level. The other 3 boxes did not fail until they reached the 0.5 G rms level. Then, all three failed at 26 seconds, 45 seconds, and 49 seconds, respectively (See Appendix A-3).

The 8" x 4" x 4" box was loaded with 22.6% of its compression strength, or 81.36 lb. Failure was consistent throughout the boxes at the 0.4 G rms level. Time to failure ranged between 76-189 seconds (See Appendix A-3).

Ninety-four pounds was loaded on top of the 10" x 6" x 4" samples, representing 22.6% of the actual compression strength. These boxes, like the others, each survived 300 seconds at 0.2 G rms, 300 seconds at 0.3, and failed at the 0.4 G rms level between 100-234 seconds. This showed very consistent data between the boxes, loaded with 22.6% of the compression strength, with failures at 0.4 and 0.5 G rms levels. At 22.6% load the boxes did sustain 0.2 G rms for 300 seconds, 0.3 G rms for 300 seconds, and some 0.4 G rms or up to 0.5 G rms for 49 seconds (6" x 4" x 4" box) (See Appendix A-3). Marcondes (1996) found for a dead load ranging from 24-42% of the compression strength, boxes failed at 0.3 G rms. This correlates to the findings of this research.

33% Mean Lab Compression Strength

Consistent failure was seen in the 6" x 4" x 4" box size loaded with 33% of the compression strength. All five boxes survived 300 seconds at 0.2 G rms levels and 300 seconds at the 0.3 G rms level and failed before the vibration table reached full level at 0.4 G rms.

The 8" x 4" x 4" sized boxes were loaded with 119 lb., or 33% of the average lab determined compression strength. With a 33% load, all 5 boxes survived the 0.2 G rms level for 300 seconds. Four of the five boxes failed at the 0.3 G rms level, the failure times ranged from 51-144 seconds. The last box survived 300 seconds at the 0.3 level and failed 3 seconds into the 0.4 level (See Appendix A-4).

All of the 15 boxes failed somewhere within the 0.3 and 0.4 G rms levels with a 33% load. It was found that RSCs of these sizes can sustain 0.2 G rms levels with a 33% load (See Appendix A-4). Again, for a dead load between 24-42%, the maximum G rms level before failure found by Marcondes (1996) was 0.3 G rms. This is in the same range as what this study found.

<u>50% Mean Lab Compression Strength</u>

Next, new boxes were each loaded with half of the average compression strength found in the laboratory compression tests. Four of the 6" x 4" x 4" sized boxes failed at the 0.2 G rms level, two before even 30 seconds (28, 29 seconds), and the other tow in approximately 1.5 minutes (84 and 98 seconds). The fifth box survived 300 seconds at 0.2 G rms, but collapsed before reaching full level at 0.3 G rms (See Appendix A-5).

The 8" x 4" x 4" boxes indicated similar results. Four of the boxes loaded with 180 lb. (1/2 the calculated lab compression strength) failed before reaching full level at 0.2 G rms. The last box failed 14 seconds after reaching full level at 0.2 G rms (See Appendix A-5).

The 10" x 6" x 4" boxes mitigated the 50% load slightly better. One box failed after 13 seconds at the 0.2 level, the others failed at 37, 38, and 72 seconds. The last box survived 300 seconds at 0.2 and failed before the full level at 0.3 G rms (See Appendix A-5).

All box sizes failed within the 0.2, and 0.3 G rms levels with 50% of the weight from the lab determined compression strength. Although Marcondes (1996) did not experiment with a 50% load on the boxes, at a 40% load he found the maximum G rms level, before failure, to also be 0.2 G rms.

Overall Vibration Level vs. Percent Load

Figure 5 shows the average G rms level at failure versus the percentage load of actual compression strength for all boxes. Data points lying between G rms levels were obtained by first dividing the failure time (in seconds) by total time, 300 seconds. For instance, if a box survived 150 seconds at the 0.5 G rms level, the plotted point would be:

$$0.5 + 150/300, \text{ or } 0.55 \text{ G rms.} \qquad (3)$$

For each box size, the average for all samples was calculated in order to plot the G rms in Figure 5.

In comparing the research found in this study to the ASTM D4169-96 "F" factors, the estimations are very close. For an "F" factor of 10, the test specification for assurance level 1 calls for 0.73 G rms level to be used in testing. In this research, the SRF correlated to 0.6, 0.65 G rms. For an "F" factor of 7, the assurance level 2 test specification recommends 0.53 G rms be used in testing. In this study, the same, 0.53 G rms level was found for a dynamic strength reduction factor of 7. Finally, for an "F" factor of 5, the test specification calls for testing at 0.37 G rms. In this study, the SRF was found to be approximately 0.45 G rms.

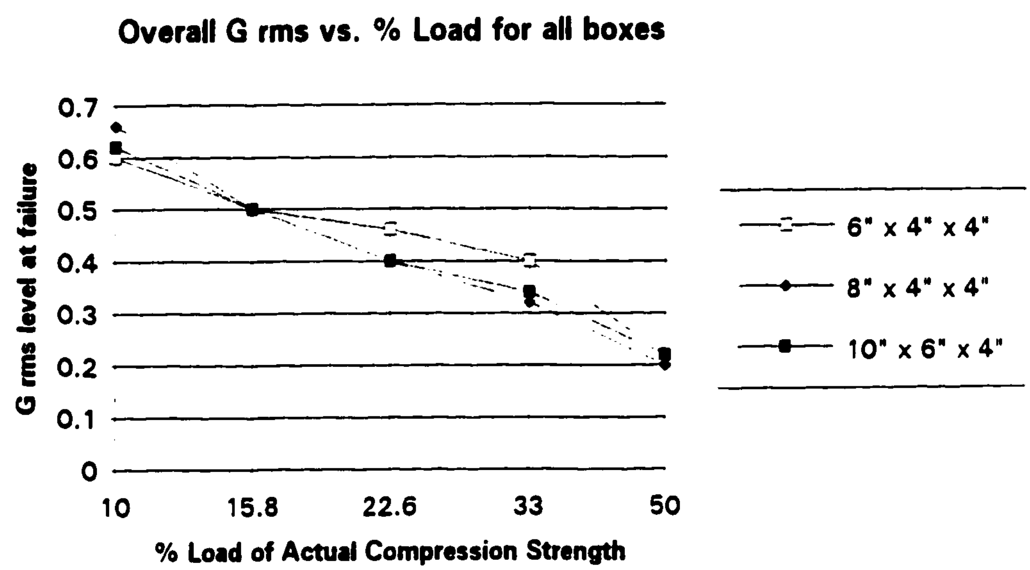

Figure 5. Overall G rms level vs. % Load for all Boxes

<u>Resonance of the Boxes Before Failure</u>

Resonance of the 75 boxes was monitored with the use of a PCB model A353-B15 accelerometer mounted vertically (in the top to bottom axis) to the upper most weight with hot melt adhesive in the aluminum piston. Resonance was determined by identifying the frequency where the response acceleration was at its highest. Figure 6 shows a typical response of the load when the vibration table input was 0.2 G rms. The highest transmissibility is the frequency of 34 Hz.

It was expected that the load and resonant frequency would have an inverse relationship, as Kusza and Young (1974) found. This was the case for the two smaller box sizes (6" x 4" x 4" and 8" x 4" x 4"). However, with the 10" x 6" x 4" box, this did not occur. The 10" x 6" x 4" box had an increase in resonant frequency as the load increased from 15.8% to 22.6%. This was true for the 0.2 and 0.4 G rms levels; the 0.3 G rms level had the same resonant frequency (See Figures 7, 8, 9).

The 6" x 4" x 4" boxes also had an increase in the resonant frequency at the 0.4 G rms level when loaded with 33% of the average compressive strength. However, this could be attributed to the system running at a lower G rms level as the controller ramped the vibration table up to full level. Because the machine cannot go directly to a high G rms level, it must first run through the lower G rms levels to build up to the higher levels. At lower G rms levels, higher resonant frequencies are recorded. Because the machine was still running at lower levels, and had not reached the full 0.4 G rms level, higher resonant frequencies were recorded. The readout on the controller also has a slight lag

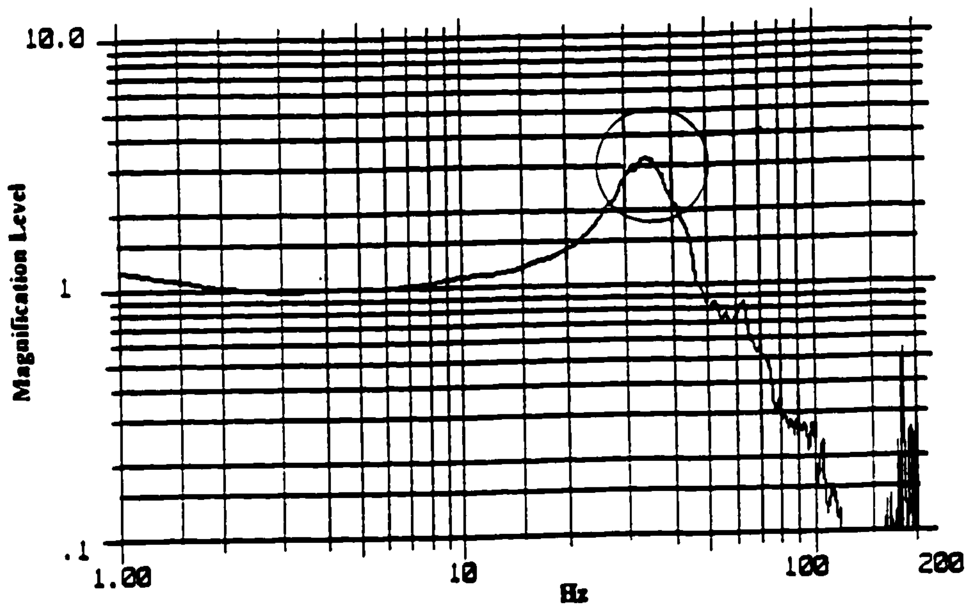

Figure 6. Typical resonant frequency response

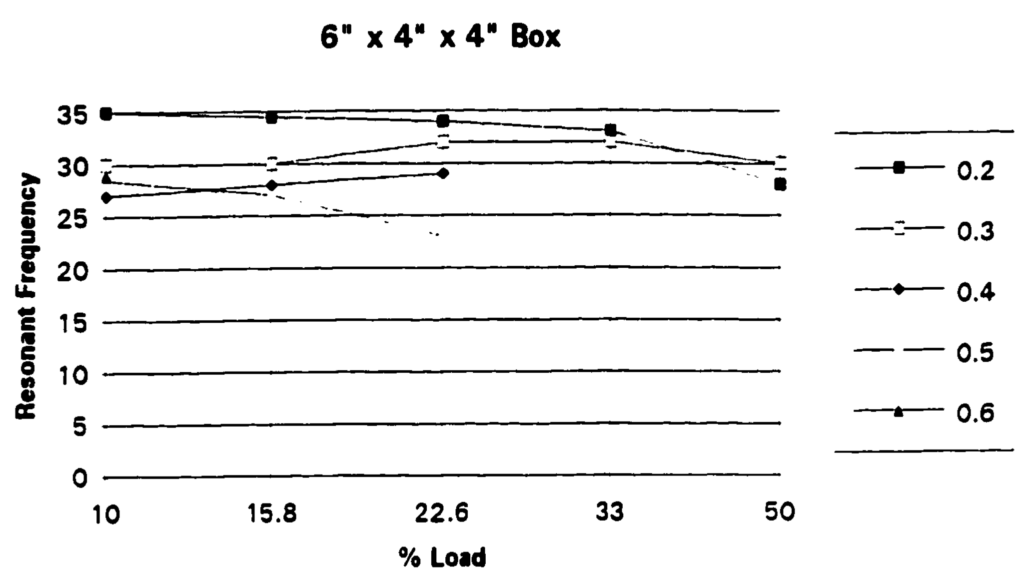

Figure 7. 6" x 4" x 4" Box resonance

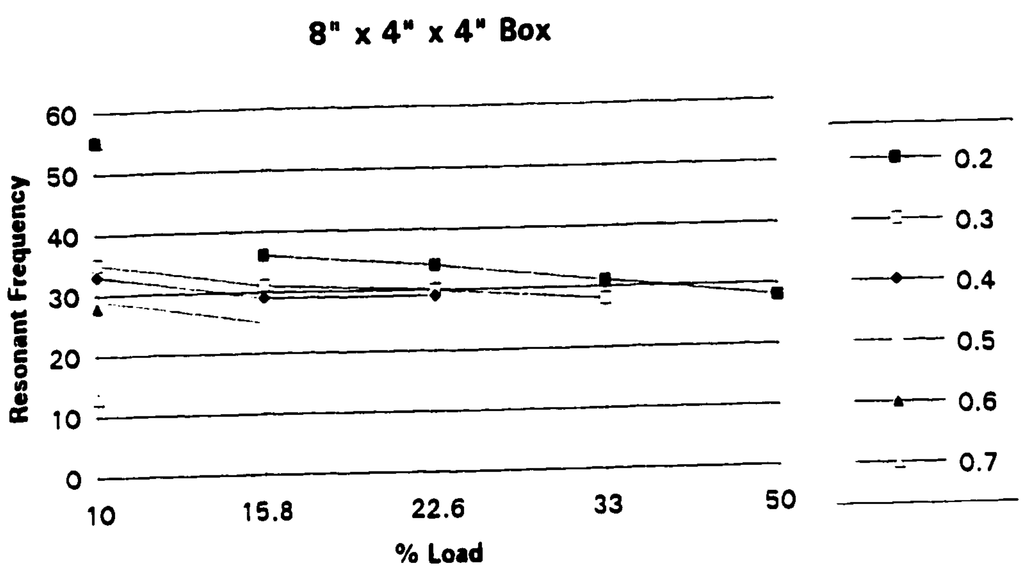

Figure 8. 8" x 4" x 4" Box resonance

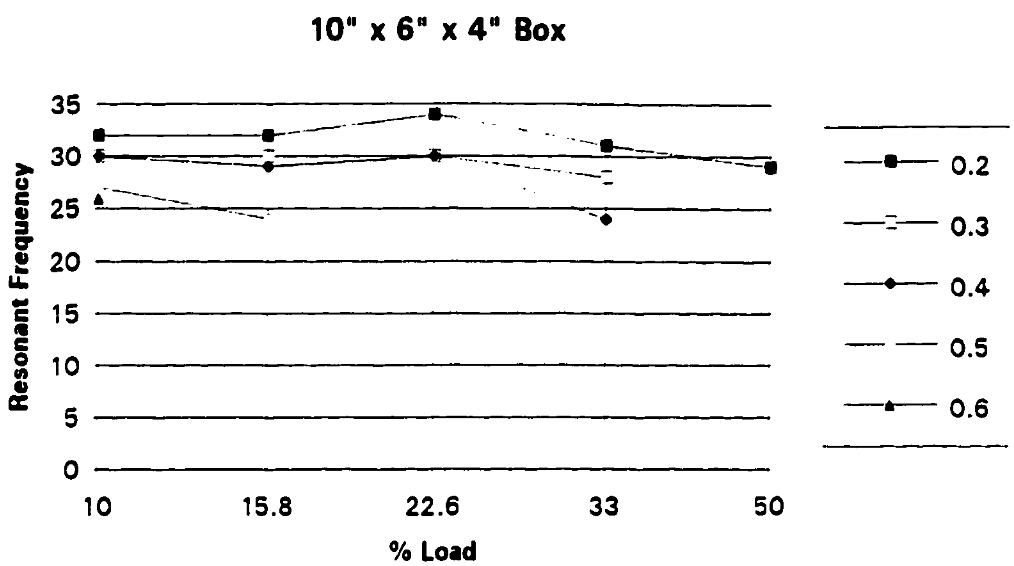

Figure 9. 10" x 6" x 4" Box resonance

time from the actual G rms level the table is running. In general, at higher G rms levels, lower resonant frequencies were recorded before failure.

Another interesting characteristic seen throughout the transmissibility plots was an antiresonance (a dip in the response spectrum), which had a frequency of approximately 20 Hz (See Figure 10). The antiresonance became apparent at the 0.3 G rms levels and above in all of the box sizes. Because it reoccurred between 18-20 Hz, the fixture was suspected of causing it.

To test the fixture, a 32 square inch area cushion (expanded polyethylene laminate, 1.7 PCF density) which was 4 inches thick was placed under a load to simulate a box being tested. The cushion was placed in the template (used to hold the boxes), and the aluminum piston was lowered down on top of it with an 80 lb. load. Then, five minutes were run at each G rms level, as was done with the corrugated RSCs. The same antiresonance showed up on the cushion fixture at the 0.3, 0.4, and 0.5 G rms levels at the same frequency 18-20 Hz. From these tests, the antiresonance was deduced to be caused by the fixture.

Next, the fixture was examined in an attempt to isolate the antiresonance. An accelerometer was mounted on the wall of the aluminum piston to measure response to excitation. The accelerometer was connected to a GHI CAT system where a Shock Response Spectrum (SRS) plot was used to display the response to the excitation. The excitation was caused by a rubber mallet striking the walls of the piston. This produced the first peak at 40 Hz, indicating that the walls resonated at above the 20 Hz seen in the

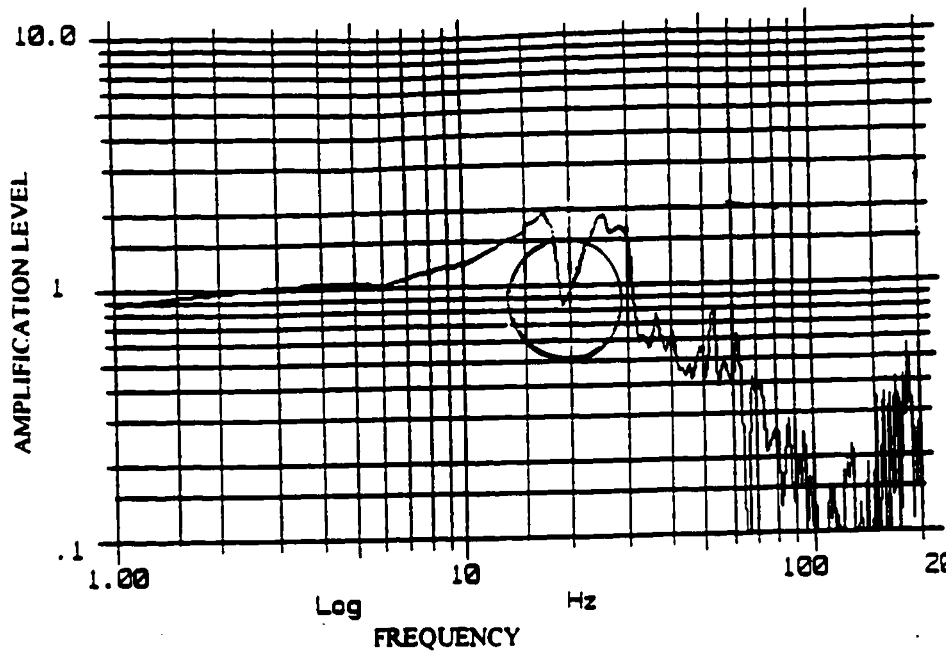

Figure 10. Typical antiresonance

antiresonance during testing. Because the first peak of resonance was seen at 20 Hz higher than the antiresonance which occurred in testing, this was deduced not to be the cause of the antiresonance. Most likely, the antiresonance was due either to friction between the "piston" and guide assembly or a low frequency ringing from the weights or rods holding the weights.

Summary

The failure patterns of the boxes were very consistent. As expected, the percentage top load had an inverse relationship with the G rms vibration level at which they failed. For RSCs sized between 6" x 4" x 4" and 10" x 6" x 4" loaded with 10% of the box compression strength, failure can be expected during the 0.6 G rms level. For boxes of the same size loaded with 15.8% of the compression strength the failure should be expected to occur during the 0.5 G rms level. When loaded with 22.6% of the compression strength the boxes most likely will fail before reaching the 0.5 G rms level. For a 33% load, failure can be expected to occur before full level of 0.4 G rms. When loaded with 50% of the compression strength, failure can be expected to occur shortly into the 0.2 G rms level. Fails caused by vibration at a certain G rms level can be related to trip roughness. For example, a "rough trip" can be associated with 0.6 G rms. So a strength reduction factor of 10 should be used to determine the lab compression strength required for an RSC to survive this ride. Using this factor, if a weight of *w* lb. is expected to be placed on the box in transport, this box should have a lab compression strength of 10 x *w* (lb.).

It should be noted that vibration levels commonly called for in test specifications, as well as those used in this research, represent accelerated tests at higher G rms levels than encountered on actual road trips. Because it is not feasible to have laboratory tests continue for several days, as trips often due, vibration levels are increased and the box is subjected to a few hours at higher vibration levels to simulate the road trip.

Recommendations

In distribution, boxes are often subjected to extreme temperature and humidity levels. In this study, all boxes were preconditioned and then conditioned at standard conditions. More studies should be completed on boxes subjected to high humidity, chilled conditions, or others. Also, boxes other than RSCs, and RSCs of other dimensions and materials, should be tested for possible application of these results because dynamic response would be different since they are influenced by the dynamics of the system.

Application

This research in determining a dynamic strength reduction factor (DSRF) has many useful applications. The DSRF can be used to estimate the lab compression strength necessary for a corrugated box to support a load when in distribution. Figure 14 shows overall G rms level vs. Load and DSRF for all boxes. This can be applied in designing and testing corrugated fiberboard boxes. A study of the expected distribution environment will allow an estimation of the G rms level anticipated. Figure 11 can be used to find an approximate DSRF. For example: If in transport, stacks of n boxes are expected, then the force applied to the lowest box in the stack is given by:

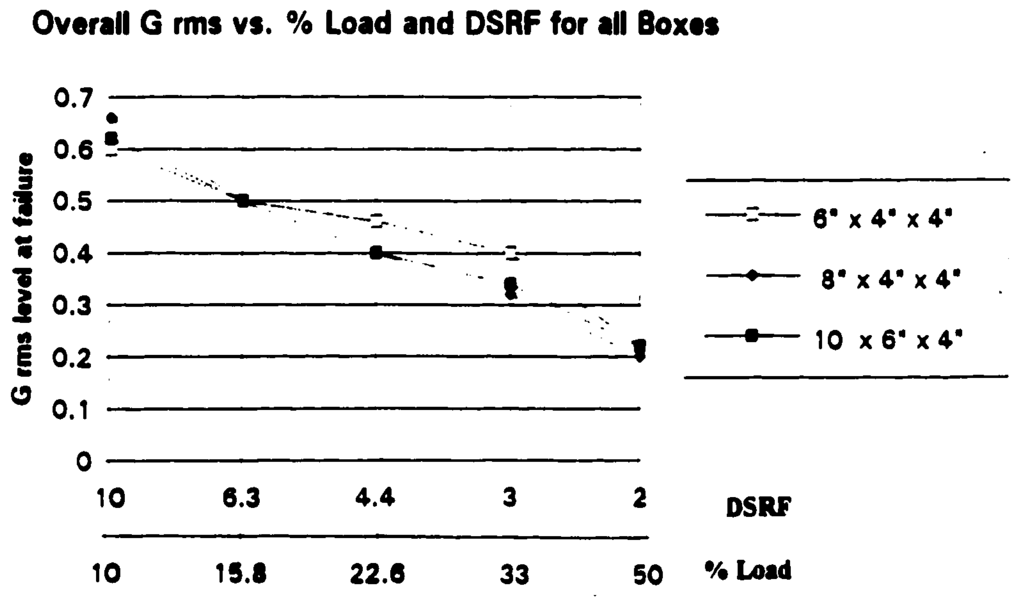

Figure 11. Overall G rms vs. % Load and DSRF for all Boxes

$$F = (n-1)\,(w) \tag{4}$$

where F= force on bottom box (lb.), w= weight of each box (lb.). From this, laboratory compression strength required can be calculated by

$$(F) \times (DSRF). \tag{5}$$

This compression strength required can then be used for design (with the use of McKee's formula) and for testing using a compression tester. For example, a company which uses 0.53 G rms to conduct a short laboratory vibration test to simulate a long truck haul on 10 boxes weighing 10 lb. each. The force on the bottom box would be:

$F = (10-1) \times (10 \text{ lb.}) = 90 \text{ lb.}$

Then using Figure 2, the DSRF can be determined to be 7. Using the formula (F) x (DSRF) = (7) x (90 lb.) = 630 lb. Therefore, the box needs to have a compression strength of at least 630 lb.

References

Adams, A.R. (1987). The effect of transient vibration on the top-to-bottom compressive strength of unitized corrugated shipping containers. Thesis for M.S. Michigan State University, East Lansing, MI.

American Society for Testing and Materials (1994). D-4169 - Performance testing of shipping containers and systems, in Selected ASTM Standards on Packaging (4th ed.). Philadelphia, PA: Author. 237-247.

American Society for Testing and Materials (1996). D-4169 - Performance testing of shipping containers and systems. Philadelphia, PA.

Crofts, M.S. (1989). The effect of simulated handling on the compression performance of corrugated fiberboard containers. Thesis for M.S. Michigan State University, East Lansing, MI.

Godshall, W.D. (1968). Effects of vertical dynamic loading on corrugated fiberboard containers. General Technical Report FPL 94. Forest Products Laboratory, Forest Service. U.S. Department of Agriculture.

Guins, S.G. (1975). Notes on package design. Guins, Okemos, Michigan.

International Safe Transit Association 1996. Preshipment test procedures. Procedure 2 and 2A. East Lansing, Michigan.

Kellicutt, K.Q., and Landt. E.F. (1951). Safe stack life of corrugated boxes. Fibre Containers, 9: 1-5.

Kusza, T.J. and Young, D.E. (1974). Package development. Testing, 11/12: 55.

Langlois, M.M. (1989). Compression performance of corrugated fiberboard shipping containers having fabrication defects: fixed versus floating platens. Thesis for M.S. Michigan State University, East Lansing, MI.

Marcondes, J.A. (1996). Virgin vs. recycled corrugated: similar compression strengths. Packaging Technology & Engineering, 1: 49-52.

Marcondes, J.A., Feather, W.H. (1992). Assessment of vibration levels on truck shipments. Transactions, Volume 19, No.1/EMCP. 22-27.

McKee, R.C., Gander, J.W., and Wachuta, J.R. (1963). Compression strength formula for corrugated boxes. Paperboard Packaging, 8: 144-159.

Newland, D.D., (1984). Random vibration and spectral analysis, Longman Group Ltd., England.

Ostrem, F.E. & Godshall, W.D. (1979). An Assessment of the Common Carrier Shipping Environment. General Technical Report FPL22, Forest Products Laboratory, Forest Service, U.S. Department of Agriculture.

Pennington, D. (1966). Basic Shock and Vibration Data, Environmental Quarterly, 5: 1-12.

Soroka, W. (1995). Corrugated fiberboard. Fundamentals of Packaging Technology, 355-383.

Surber, R.A. & Catlin, A.H. (1982). Estimating the effects of interior on corrugated box stacking strength. Packaging Technology, 3: 15-23.

Technical Association of the Pulp and Paper Industry (1992). Standard test method for bursting strength of corrugated and solid fiberboard. T 810 om-92.

Urbanik, T.J. (1990). Proceedings, 61st Shock and vibration symposium. Pasadena, CA. Jet Propulsion Laboratory, 1, 253-274.

APPENDICES

APPENDIX 1

Top Loaded Box Failure Data

Table A-1

Maximum G rms level sustained and respective failure time at that level, with 10% load

Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
6 x 4 x 4	11	10	0.6	28	2	238
6 x 4 x 4	12	10	0.6	29	2	250
6 x 4 x 4	13	10	0.6	29	2	185
6 x 4 x 4	14	10	0.6	29	2	300
6 x 4 x 4	15	10	0.6	29	2	211
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
8 x 4 x 4	16	10	0.7	14	1	151
8 x 4 x 4	17	10	0.7	11	1	76
8 x 4 x 4	18	10	0.6	29	2	139
8 x 4 x 4	19	10	0.6	28	2	164
8 x 4 x 4	20	10	0.7	13	1	53
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
10 x 6 x 4	21	10	0.6	30-39	2	269
10 x 6 x 4	22	10	0.6	23	2	193
10 x 6 x 4	23	10	0.6	18	2	152
10 x 6 x 4	24	10	0.7	18	2	54
10 x 6 x 4	25	10	0.6	28	2	155

Table A-2

Maximum G rms level sustained and respective failure time at that level, with 15.8% load

Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
6 x 4 x 4	1	15.8	0.5	28	6	115
6 x 4 x 4	2	15.8	0.5	29	2	116
6 x 4 x 4	3	15.8	0.5	27	2	86
6 x 4 x 4	4	15.8	0.5	27	2	77
6 x 4 x 4	5	15.8	0.5	26	4	114
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
8 x 4 x 4	26	15.8	0.5	17	2	90
8 x 4 x 4	27	15.8	0.5	29	2	84
8 x 4 x 4	28	15.8	0.5	23-29	2	125
8 x 4 x 4	29	15.8	0.5	26-28	2	111
8 x 4 x 4	30	15.8	0.5	28	2	132
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
10 x 6 x 4	31	15.8	0.5	15 & 22	2	71
10 x 6 x 4	32	15.8	0.5	27	2	82
10 x 6 x 4	33	15.8	0.5	27-29	2	91
10 x 6 x 4	34	15.8	0.5	27	2	79
10 x 6 x 4	35	15.8	0.5	17	2	79

Table A-3

Maximum G rms level sustained and respective failure time at that level, with 22.6% load

Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
6 x 4 x 4	6	22.6	0.5	15	2	26
6 x 4 x 4	7	22.6	0.5	18	2	49
6 x 4 x 4	8	22.6	0.5	18/25	2	45
6 x 4 x 4	9	22.6	0.4	29	2	271
6 x 4 x 4	10	22.6	0.4	29	2	228
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
8 x 4 x 4	36	22.6	0.4	27-29	2	100
8 x 4 x 4	37	22.6	0.4	29	2	96
8 x 4 x 4	38	22.6	0.4	28-30	2	125
8 x 4 x 4	39	22.6	0.4	27-29	2	76
8 x 4 x 4	40	22.6	0.4	29	2	198
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
10 x 6 x 4	41	22.6	0.4	36-39	3	122
10 x 6 x 4	42	22.6	0.4	29	3	101
10 x 6 x 4	43	22.6	0.4	27-30	3	109
10 x 6 x 4	44	22.6	0.4	26	2	100
10 x 6 x 4	45	22.6	0.4	29	3	234

Table A-4

Maximum G rms level sustained and respective failure time at that level, with 33% load

Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
6 x 4 x 4	46	33	0.3 0.4	29 -	3 4	Survived 300s before full level
6 x 4 x 4	47	33	0.3 0.4	33 -	3 -	Survived 300s before full level
6 x 4 x 4	48	33	0.3 0.4	34 -	3 -	Survived 300s before full level
6 x 4 x 4	49	33	0.3 0.4	29 -	3 -	Survived 300s before full level
6 x 4 x 4	50	33	0.3 0.4	33 -	3 -	Survived 300s before full level
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
8 x 4 x 4	51	33	0.3	29	3	144
8 x 4 x 4	52	33	0.4	25	3	3
8 x 4 x 4	53	33	0.3	29	3	76
8 x 4 x 4	54	33	0.3	26	3	140
8 x 4 x 4	55	33	0.3	27-29	3	51
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
10 x 6 x 4	56	33	0.3	29	3	125
10 x 6 x 4	57	33	0.3 0.4	30 -	4 -	Survived 300s before full level
10 x 6 x 4	58	33	0.3	26	2	65
10 x 6 x 4	59	33	0.4	29	3	33
10 x 6 x 4	60	33	0.3	27	3	88

Table A-5

Maximum G rms level sustained and respective failure time at that level, with 50% load

Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
6 x 4 x 4	61	50	0.2	22	3	28
6 x 4 x 4	62	50	0.2	30	3	84
6 x 4 x 4	63	50	0.2 0.3	30 -	4 -	Survived 300s before full level
6 x 4 x 4	64	50	0.2	29	4	98
6 x 4 x 4	65	50	0.2	29	4	29
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
8 x 4 x 4	66	50	0.2	-	-	before full level
8 x 4 x 4	67	50	0.2	-	-	before full level
8 x 4 x 4	68	50	0.2	-	-	14
8 x 4 x 4	69	50	0.2	-	-	before full level
8 x 4 x 4	70	50	0.2	-	-	before full level
Box Size	Box #	Load %	G rms Level	Resonance	Amplitude	Failure (s)
10 x 6 x 4	71	50	0.2 0.3	30 -	4 -	Survived 300s before full level
10 x 6 x 4	72	50	0.2	26-29	3	72
10 x 6 x 4	73	50	0.2	29	4	37
10 x 6 x 4	74	50	0.2	36	3	13
10 x 6 x 4	75	50	0.2	24-29	3	38

APPENDIX 2

Bursting Strength Data

Table A-6

Bursting Strength of the 6" x 4" x 4" box

Sample Number	Burst Strength (lb./in^2)
1	195
2	234
3	225

Mean = 218
Standard deviation = 20.4

Table A-7

Bursting Strength of the 8" x 4" x 4" box

Sample Number	Burst Strength (lb./in^2)
1	225
2	242
3	270

Mean = 245.67
Standard deviation = 22.72

Table A-8

Bursting Strength of the 10" x 6" x 4" box

Sample Number	Burst Strength (lb./in^2)
1	205
2	215
3	195

Mean = 205
Standard deviation = 10

APPENDIX 3

Edge Crush Test (ECT) Data

Table A-9

Edge Crush Test Data of the 6" x 4" x 4" boxes

Test Number	Load at Fail (lb.)
1	34.8
2	35.9
3	35.1
4	29.7
5	28.4

Mean = 32.78
Standard deviation = 3.46

Table A-10

Edge Crush Test Data of the 8" x 4" x 4" boxes

Test Number	Load at Fail (lb.)
1	41.6
2	42.9
3	38.9
4	41.3
5	45.8

Mean = 42.1
Standard deviation = 2.52

Table A-11

Edge Crush Test Data of the 10" x 6" x 4" boxes

Test Number	Load at Fail (lb.)
1	35.5
2	35.7
3	35.2
4	32.4
5	37.5

Mean = 35.26

Standard deviation = 1.83